

## **Influence of Tillage and Nutrient Sources on Yield Sustainability and Soil Quality under Sorghum–Mung Bean System in Rainfed Semi-arid Tropics**

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**Abstract:** The crop production in rainfed semi-arid tropical (SAT) Alfisols is constrained by low soil organic matter, poor soil fertility, soil structural infirmities, and scarce moisture availability. To offset some of these constraints, a long-term study of tillage [conventional (CT) and reduced (RT)] and conjunctive nutrient-use treatments was conducted in SAT Alfisol at Hyderabad, India, under sorghum–mung bean system. The order of performance of the treatments in increasing the sorghum yield was 2 Mg gliricidia loppings + 20 kg nitrogen (N) through urea (T4) (93.2%) > 4 Mg compost + 20 kg N through urea (T3) (88.7%) > 40 kg N through urea (T2) (88.5%) > 4 Mg compost + 2 Mg gliricidia loppings (T5) (82.2%). In the case of mung bean, where half as much N was applied as was to the sorghum, the order of performance of the treatments in increasing the grain yields was T3 (63.6%) > T5 (60.3%) > T4 (58.0%) > T2 (49.6%). Tillage significantly influenced the hydraulic conductivity only, whereas the conjunctive nutrient-use treatments significantly influenced the predominant physical, chemical, and biological soil-quality parameters. Among the conjunctive nutrient-use treatments, T5 was found to be superior in influencing the majority of the soil-quality parameters and increased the organic carbon by 21.6%, available N by 24.5%, dehydrogenase activity by 56.1%, microbial biomass carbon by 38.8%, labile carbon by 20.3%, and microbial biomass nitrogen by

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38.8% over the unamended control and proved superior most in improving soil quality.

**Keywords:** Alfisols, conventional and reduced tillage, crop yield sustainability, farm-based organics, soil fertility, soil-quality indicators

## INTRODUCTION

Alfisols are the most abundant soils in the semi-arid tropics and cover nearly 16% of the tropics and 33% of the semi-arid tropics (SAT). These soils occur extensively in southern Asia, western and central Africa, and many parts of the South America, particularly northeastern Brazil (Cocheme and Franquin 1967). In general, these soils are shallow, with a compacted subsurface layer that inhibits root development and water percolation. The loamy sand texture of the topsoil and predominance of kaolinite among the clay minerals make them structurally inert (Charreau 1977). Structural instability of these soils makes them susceptible to crusting and hard setting when rain alternates with dry spells (Bansal, Awadhwai, and Mayande 1987). The soils are also low in organic carbon (C) content ( $<5.0 \text{ g kg}^{-1}$ ) and consequently poor in fertility (Kampen and Burford 1980; El-Swaify, Singh, and Pathak 1983). This may be primarily attributed to (i) loss of topsoil and associated fractions of organic matter and nutrients; (ii) poor return of the crop residues back to the soil; and (iii) temperature-mediated and tillage-influenced fast oxidation of organic matter entrapped in microaggregates. Consequently, these soils encounter diversity of constraints on account of physical, chemical, and biological quality (Lal 1998; Sharma et al. 2005) and lead to low productivity. Farmers in these rainfed SAT regions use small amounts of inorganic fertilizer because of extreme poverty and escalating costs of inorganic fertilizers. To meet these challenges and to provide good soil and nutrient management options using farm resources, it has become absolutely necessary to look for innovative alternative soil and nutrient management options that could (i) enhance the organic carbon (C) in soil; (ii) improve soil fertility and overall soil health; (iii) reduce the dependence of the small and marginal farmers on costly fertilizer inputs; and (iv) sustain greater yields on a long-term basis. Conservation agriculture techniques of zero or reduced tillage, green manuring, recycling of crop residues, etc., have proved effective in irrigated and temperate regions (Unger 1990). Such innovative options have not been extensively studied over a long-term period in rainfed SATs having severe climatic and edaphic constraints. Research on zero and reduced tillage has also not been much taken up in SAT regions mostly in developing countries because of (i) difficulty in weed control; (ii) less water infiltration in soil owing to compacted conditions;

and (iii) lack of availability of appropriate seeding devices suiting to reduced tillage conditions. The inclusion of farm-based organics as low-cost nutrient source has also not been explored much. Considering these facts, the present study was undertaken to (i) evaluate suitable low-cost, farm-based, conjunctive nutrient-use sources in terms of crop yield and sustainability under conventional and reduced tillages and (ii) monitor their long-term influence on soil physical, chemical, and biological soil-quality parameters with special emphasis on soil fertility.

## MATERIALS AND METHODS

### Experimental Details

A long-term experiment was conducted during 1998–2005 with sorghum (cv ‘CSH-9’) and mung bean (cv ‘ML-267’) as test crops at Hayathnagar Research Farm of Central Research Institute for Dryland Agriculture, Hyderabad, situated at 17° 18’ N latitude and 78° 36’ E longitude at an elevation of 515 m above mean sea level. This region falls in the SAT zone and experiences hot summers and moderate winters. The average annual rainfall of this region is about 750 mm, and the annual evapotranspiration is about 1750 mm. Soils of the experimental field belong to the Hayathnagar series (Typic Haplustalf) and are slightly acidic to neutral in reaction (pH 6.5) with sandy loam texture and increasing clay content in the lower horizons. Soils were initially low in organic C and available nitrogen (N) [potassium permanganate (KMnO<sub>4</sub>) oxidizable N] and medium in available phosphorus (Olsen’s P) and potassium (1 N ammonium acetate–extractable K). The experiment was conducted in a split-plot design with two tillage [conventional (CT) and reduced (RT)] and five low-cost, farm-based, conjunctive nutrient-use treatments using three replicates. Sorghum [*Sorghum bicolor* (L.) Moench] and mung bean [*Vigna radiata* (L.) Wilczek] were used as test crops. Sorghum strips were rotated with mung bean strips with treatments consistent from year to year. Conventional tillage consisted of two plowings before planting + one plow planting + harrowing + operation for top-dressing (this includes summer tillage/off-season tillage), whereas reduced tillage comprised of plow planting + operation for top-dressing of N using light implements such as pick axes. The five conjunctive nutrient-use treatments equivalent to 40 kg N ha<sup>-1</sup> applied to sorghum crop were composed of control (no N) (T<sub>1</sub>), 40 kg N through urea (T<sub>2</sub>), 4 Mg compost + 20 kg N (T<sub>3</sub>), 2 Mg gliricidia loppings (*Gliricidia maculata*) + 20 kg N (T<sub>4</sub>), and 4 Mg compost + 2 Mg gliricidia loppings (T<sub>5</sub>). Mung bean crop received half of the dose of N (equivalent to 20 kg N ha<sup>-1</sup>) applied to sorghum. Compost (N content = 5 g kg<sup>-1</sup>) was spread before sowing the crops. In the case of the sorghum

crop, fertilizer N in the form of urea was applied in two equal splits: one half as basal at the time of sowing and another half 30–35 days after sowing (DAS), whereas in mung bean, it was applied in a single split as basal dose. Fresh loppings of glyricidia (an N-fixing tree containing  $33.3 \text{ g kg}^{-1}$  N on dry-weight basis in leaves and twigs) were applied to both the crops at 30–35 DAS as per the treatments along with second split of N. Recommended level ( $30 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$ ) of P as single superphosphate was broadcasted equally to both sorghum and mung bean crops uniformly before sowing. Weeds were controlled by a combination of hand weeding and harrowing depending upon the situation. The compost used in the treatments was prepared in the farm itself by using a mixture of various farm-based residues and cattle dung. Every year, crops were seeded during the onset of monsoon in the month of June. Mung bean was harvested in the month of August and sorghum in October. The grain yields were recorded for each year from 1998 to 2005, except for the year 2003, when the crop failed because of severe drought.

Agronomic efficiency (AE), a parameter representing the ability of the plant to increase yield in response to per unit N applied, was computed based on the average grain yield data using the following relationship:

$$\text{AE} = \frac{(Y_{\text{TP}} - Y_{\text{CP}})}{\text{FN}}$$

where  $Y_{\text{TP}}$  is the grain yield ( $\text{kg ha}^{-1}$ ) of treated plot,  $Y_{\text{CP}}$  is grain yield of control plot, and FN is the applied dose of fertilizer N ( $\text{kg ha}^{-1}$ ).

In rainfed agriculture, as the magnitude of the yield is predominantly influenced by rainfall besides other factors, the computation of the sustainability of the yield becomes more important than simple mean (FAO 1989). In the present study, the sustainability in yield was monitored in terms of sustainable yield index (SYI), which represented minimum guaranteed yield in response to nutrient management treatment as a percentage of the maximum observed yield with high probability. This index was calculated as follows:

$$\text{SYI} = \frac{Y - \sigma}{Y_{\text{max}}}$$

where  $Y$  is the average yield of the treatments across the years,  $\sigma$  is the treatments standard deviation, and  $Y_{\text{max}}$  was the maximum observed yield over years in the experiment (Singh et al. 1990).

### Soil Sampling and Analysis

Soil samples from 0–20 cm deep were collected from the experimental site after the eighth cropping season (during 2005) of the study and were passed through 8, 4.75, and 2 mm sieves. Soil samples passed through the

8-mm sieve and retained on the 4.75-mm sieve were used for aggregate analysis. Soil samples passed through the 2-mm sieve were used for analyzing chemical and biological parameters. A portion of the 2-mm sieved sample was further ground and passed through the 0.2-mm sieve for organic C estimation. The soil reaction (pH) and electrical conductivity (EC) were measured in 1:2 soil–water suspension (Rhoades 1982), organic C by wet oxidation using sulfuric acid ( $\text{H}_2\text{SO}_4$ ) + potassium dichromate ( $\text{K}_2\text{Cr}_2\text{O}_7$ ) (Walkley and Black, 1934), available N by alkaline- $\text{KMnO}_4$  method (Subbaiah and Asija 1956), available P by 0.5 M sodium bicarbonate ( $\text{NaHCO}_3$ ) method (Olsen et al. 1954), and available K and exchangeable calcium (Ca) and magnesium (Mg) by neutral normal ammonium acetate method (Hanway and Heidal 1952). Micronutrient cations [viz., zinc (Zn), iron (Fe), copper (Cu), and manganese (Mn)] were extracted using diethylenetriaminepentaacetic acid (DTPA)–calcium chloride ( $\text{CaCl}_2$ )–triethanolamine (TEA) reagent (pH 7.3) (Lindsay and Norvell 1978), and concentrations were measured using inductively coupled plasma–optical emission spectroscopy (ICP-OES) simultaneous system (GBC-Australia), and boron (B) was estimated using DTPA–sorbitol extraction (Miller, Vaughan, and Kutoby-Amacher 2000).

Bulk density (BD) was measured by the soil core method (Blake and Hartge 1986), and hydraulic conductivity (HC) was measured by constant head method (Klute 1965). The distribution of aggregate size was determined using a wet-sieving technique (Yoder 1936), and mean weight diameter (MWD) was computed (van Bevel 1949). The soil samples were placed on the uppermost sieve of a nest of sieves of 4.75, 2.0, 1.0, 0.5, 0.25, and 0.1 mm in size arranged in descending order. The sieve set along with soil was subjected to the slaking action of water by moving mechanically upward and downward. Corrections were made for the coarse primary particles retained on each sieve. This was done by dispersing the material collected from each sieve with a mechanical stirrer using sodium hexa-metaphosphate as a dispersing agent and then washing the material back through the same sieve. Weight of the sand fraction retained after the second sieving was subtracted from the total weight of undispersed material retained after the first sieving to achieve the actual weight of the aggregated particles. The mean weight diameter was calculated using the equation

$$\text{MWD} = \frac{\sum_{i=1}^n X_i \times W_i}{\sum_{i=1}^n W_i}$$

where  $X_i$  is the average diameter of each particle class (mm) and  $W_i$  is the proportion by weight of the given size fraction of aggregate relating to  $X_i$ .

Soil microbial biomass C (MBC) and microbial biomass N (MBN) were determined using the chloroform fumigation incubation technique (Jenkinson and Powlson 1976; Jenkinson and Ladd 1981).

Dehydrogenase activity in the soils was measured by the triphenyl tetrazolium chloride method (TTC) (Lenhard 1956). Labile carbon (LC), which is also considered as one of the important biological soil-quality indicators, was estimated using the method suggested by Weil et al. (2003) with slight modification. In this method, moist, fresh, air-dried soil was equilibrated with 20 mL 0.01 M  $\text{KMnO}_4$  solution for 15 min, and the soil-solution suspension was centrifuged at 3000 rpm for 5 min. The absorbance was measured at 550 nm using a mini-spectrophotometer, model SL 171 (Elico Ltd., New York). While calculating, corrections were made for the moisture present in the soil sample.

### Statistical Analysis

For the crop yield data, statistical analysis was performed for the individual year as well as for all the years together using split-plot design (Snedecor and Cochran, 1989). The data on soil quality parameters were also subjected to analysis of variance (ANOVA) using the above design.

## RESULTS AND DISCUSSION

### Long-Term Effect on Crop Yields

Sorghum average grain yields over years 1998 to 2005 ranged between 586 to 2367  $\text{kg ha}^{-1}$  across the treatments irrespective of the tillage (Table 1). Effect of tillage on sorghum grain yield was significant in only 5 out of 7 years. However, the average effect of the tillage studied through pooled analyses over a period of 7 years was significant. Conventional tillage maintained 12.8% more sorghum grain yield (1629  $\text{kg ha}^{-1}$ ) compared to RT (1420  $\text{kg ha}^{-1}$ ). The highest average sorghum grain yield was recorded with T4 (1895  $\text{kg ha}^{-1}$ ) under CT. Under RT, the highest yielding treatment was observed under T3 (1580  $\text{kg ha}^{-1}$ ). Interestingly, the interactive effects of years  $\times$  tillage  $\times$  treatments were also significant. The order of superiority of the nutrient-use treatments in increasing the yield of sorghum over unamended control was T4 (93.2%) > T3 (88.7%) > T2 (88.5%) > T5 (82.2%).

In the case of mung bean, the grain yields during the years 1998 to 2005 ranged between 224 and 1438  $\text{kg ha}^{-1}$  (Table 2). The pooled effects of tillage as well as conjunctive nutrient-use treatments on mung bean grain yields were significant. Conventional tillage resulted in 11.2% more mung bean grain yield than RT. The highest mung bean grain yield under CT plots was observed in T3 (959  $\text{kg ha}^{-1}$ ), whereas under RT plots, it was under T5 (836  $\text{kg ha}^{-1}$ ). The significant yearly variations in mung

**Table 1.** Long-term effects of tillage and conjunctive nutrient management treatments on sorghum grain yields

Tillage	Nutrient-use treatments	Sorghum grain yields (kg ha <sup>-1</sup> )							SSYI	Pooled analysis
		1998	1999	2000	2001	2002	2004	2005		
Conventional tillage	T1	1067	1035	1114	900	923	795	816	0.30	950
	T2	1675	1624	1760	1680	2344	2006	1592	0.57	1812
	T3	1665	1458	1923	1617	2383	2027	1470	0.54	1792
	T4	1645	1871	2002	1950	2367	2003	1427	0.59	1895
	T5	1675	1721	1733	1700	1931	1796	1310	0.56	1696
Reduced tillage	T1	1171	888	867	750	893	704	586	0.24	837
	T2	1652	1448	1305	1434	2130	1843	1107	0.45	1560
	T3	1913	1086	1313	1458	2264	1938	1091	0.42	1580
	T4	1540	1235	1451	1542	2132	1931	1120	0.45	1564
	T5	1663	1568	1285	1550	1918	1777	1135	0.47	1556
LSD ( $P < 0.05$ )	Between tillage means	NS	118	57	120	270	35	132	0.05	28.98
	Between treatment means	121	114	106	153	192	70	71	0.03	45.82
	Between two treatment means at same tillage	NS	162	149	NS	NS	NS	101	0.04	
	Between two treatment means at same or different treatments	NS	156	136	NS	NS	NS	111	0.04	
	Years	—	—	—	—	—	—	—	—	54.22
	Years × Tillage	—	—	—	—	—	—	—	—	76.68
	Years × Treatments	—	—	—	—	—	—	—	—	121.24
	Tillage × Treatments	—	—	—	—	—	—	—	—	64.81
	Years × Tillage × Treatments	—	—	—	—	—	—	—	—	NS

*Note.* The treatments were designed to supply N equivalent to 40 kg ha<sup>-1</sup> except control.

T1 = control; T2 = 40 kg N through urea; T3 = 4 Mg compost + 20 kg N through urea; T4 = 2 Mg Gliricidia loppings + 20 kg N through urea; T5 = 4 Mg compost + 2 Mg gliricidia loppings.

**Table 2.** Long-term effects of tillage and conjunctive nutrient management treatments on mung bean grain yields

Tillage	Nutrient-use treatments	Mung bean grain yields (kg ha <sup>-1</sup> )							SSYI	Pooled analysis
		1998	1999	2000	2001	2002	2004	2005		
Conventional tillage	T1	447	847	485	517	537	711	521	0.29	581
	T2	653	1056	614	830	900	1129	962	0.45	878
	T3	827	1141	599	870	900	1438	938	0.46	959
	T4	684	1059	592	710	993	1402	901	0.42	906
	T5	780	1137	702	830	721	1386	886	0.44	920
Reduced tillage	T1	628	633	224	490	520	700	408	0.23	514
	T2	656	887	284	770	765	1288	692	0.30	763
	T3	998	792	310	760	843	1392	747	0.34	835
	T4	1021	761	418	700	743	1372	754	0.35	824
	T5	1046	912	366	880	706	1217	724	0.37	836
LSD ( $P < 0.05$ )	Between tillage means	73	93	18	NS	NS	NS	171	0.05	16.20
	Between treatment means	56	81	44	48	83	96	38	0.02	25.62
	Between two treatment means at same tillage	79	NS	62	69	117	137	54	0.02	
	Between two treatment means at same or different treatments	79	NS	56	70	148	124	97	0.03	
	Years	—	—	—	—	—	—	—	—	30.31
	Years × Tillage	—	—	—	—	—	—	—	—	42.87
	Years × Treatments	—	—	—	—	—	—	—	—	67.78
	Tillage × Treatments	—	—	—	—	—	—	—	—	NS
	Years × Tillage × Treatments	—	—	—	—	—	—	—	—	95.86

*Note.* The treatments were designed to supply N equivalent to 20 kg ha<sup>-1</sup> except control.

T1 = control; T2 = 20 kg N through urea; T3 = 2 Mg compost + 10 kg N through urea; T4 = 1 Mg Gliricidia loppings + 10 kg N through urea; T5 = 2 Mg compost + 1 Mg gliricidia loppings.



bean grain yield observed may be attributed to the climatic variations such as amount and distribution of rainfall during the crop growth period. The simultaneous combined effect of years, tillage, and treatments studied in terms of interactions were also significant. The relative order of superiority of the treatments in enhancing the mung bean grain yield over control was T3 (63.6%) > T5 (60.3%) > T4 (58.0%) > T2 (49.6%).

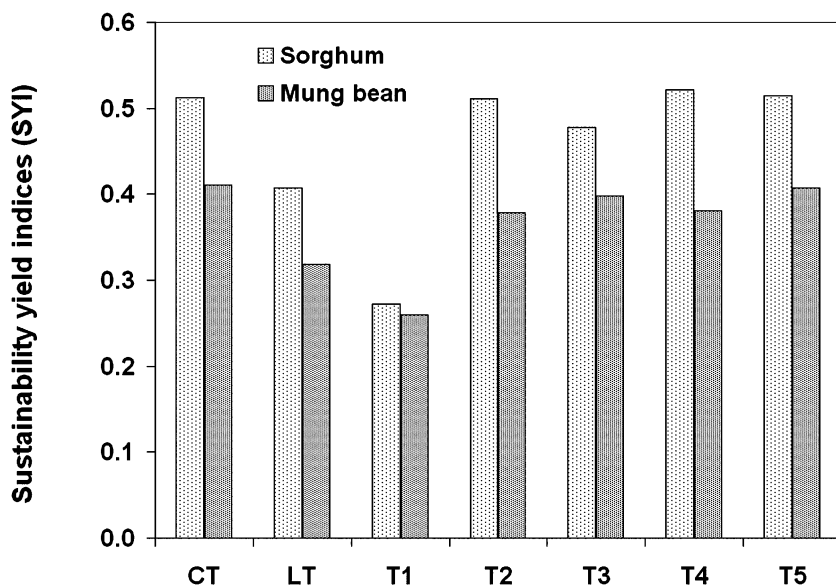
### Impact on Yield Sustainability over a Long-Term Basis

As the second outcome of the study, we monitored the impact of these treatments on the sustainability of the crop yields. Results revealed that SYI for sorghum crop under CT and RT varied from 0.30 to 0.59 and 0.24 to 0.47, respectively (Table 1). Conventional tillage showed significant higher average SYI (0.51) over the RT (0.41), thus resulting in 19.6% higher sustainability. Conjunctive nutrient-use treatments significantly influenced the SYI. Under CT, T4 recorded the highest SYI of 0.59, whereas under RT, the sole organic treatment (T5) had the highest SYI (0.47). In case of mung bean crop, the SYI varied from 0.29 to 0.46 under CT and 0.23 to 0.37 under RT (Table 2), and CT proved significantly superior to RT in terms of maintaining 22% higher SYI. Among all the treatments, irrespective of the tillage, T5 recorded the highest average SYI (0.41). Under CT, T3 recorded the highest SYI (0.46), whereas under RT, T5 had significantly higher SYI (0.37) (Figure 1).

### Crop Response, Agronomic Efficiency

Agronomic efficiency varied from 18.6 to 24.0 kg grain kg<sup>-1</sup> N under CT and 16.7 to 17.3 kg grain kg<sup>-1</sup> N under RT for sorghum crop across the treatments. In the case of mung bean crop, the corresponding values were 12.1 to 15.0 kg grain kg<sup>-1</sup> N and 8.7 to 14.2 kg grain kg<sup>-1</sup> N under CT and RT, respectively. On average, the highest agronomic efficiency of sorghum crop under CT was found in T4 (24.0 kg grain kg<sup>-1</sup> N), whereas under RT, T3 maintained the highest agronomic efficiency (17.3 kg grain kg<sup>-1</sup> N). In the case of mung bean, T3 recorded highest agronomic efficiency (15.0 kg grain kg<sup>-1</sup> N) under CT, whereas under RT, it was under T5 (14.2 kg grain kg<sup>-1</sup> N).

As all the treatment combinations except the control were designed to supply N equivalent to 40 kg N ha<sup>-1</sup> for sorghum and 20 kg N ha<sup>-1</sup> for mung bean crop; their effects on grain yield, sustainability yield indices, and agronomic efficiency were not significantly different among



**Figure 1.** Sustainability yield indices of sorghum and mung bean crops as influenced by tillage and conjunctive nutrient-use treatments on a long-term basis.

themselves, except when compared to unamended treatment. In the present study, when averaged over treatments, CT proved superior to RT in influencing the yields and sustainability yield indices of both sorghum and mung bean crops. On average, conjunctive nutrient-use treatments helped in increasing the yield of sorghum and mung bean to the extent of 82.2 to 93.2% and 49.6 to 63.6%, respectively, over control. Because the performance of the majority of the nutrient-use treatments were superior or almost comparable with T2, it is quite rational to recommend T3, T4, or T5 for both sorghum and mung bean crops (half the dose of N applied as to sorghum crop) to the growers in SAT Alfisol. Recommending these treatment options to the growers would help save almost 50% on N fertilizer without losing the yield gains.

Most of the earlier work done across the world indicates the better performance of no-tillage (or zero tillage) and RT and residue retention in terms of higher crop yields (Govaerts et al. 2006; Tsuji et al. 2006; De Vita et al. 2007). Conversely, the superior performance of CT over zero or RT has also been reported by some researchers (Baumhardt and Jones 2002; Astier et al. 2006). In the present study, CT proved superior to RT in these soils. This may be attributed to better water infiltration in the soil, desirable soil tilth for seed germination and plant growth, and less weed growth under CT. In rainfed SAT Alfisols, where crops are mostly dependent on seasonal rainfall, off-season or premonsoon primary tillage

has advantage of effective water infiltration and charging of soil profile (Bansal, Awadhwai, and Mayande 1987). There are reports indicating that to accrue the effective advantage of RT in the SAT, it is essential to maintain the crop residue on the surface as land cover (Lal 1997). In our study, the nonmaintenance of crop residue on the surface as land cover in the field after harvest could be one of the probable reasons of the poorer performance of RT. Our findings also lend support to the work done earlier by Govaerts et al. (2007) and Hulugalle and Maurya (1991). The results of the present study have also clearly demonstrated the superiority of conjunctive nutrient use in comparison to sole application of inorganic fertilizer. The direct and indirect effects of conjunctive nutrient use on crop yields could be attributed to (i) release of nutrients in synchronization with plant availability, thereby reducing losses and enhancing use efficiency, (ii) prolonged residual effect on soil fertility, (iii) rejuvenation of microbial activity in the rhizosphere by way of providing quick energy and nutrient source and overall synergistic effects (Smith and Elliott 1990; Khan et al. 2004; Bokhtiar and Sakurai 2005).

### Long-Term Influence on Soil Quality

#### Physical Soil-Quality Attributes

The long-term effects of tillage and conjunctive nutrient-use treatments on physical soil quality parameters (viz., bulk density, mean weight diameter, and hydraulic conductivity) have been monitored after 8 years and data are presented in Table 3. Significant effects of tillage were observed on only hydraulic conductivity but not on bulk density and mean weight diameter of the soil aggregate, whereas the conjunctive nutrient-use treatments significantly influenced all of these parameters. Bulk density of the soils varied from 1.73 to 1.80 and 1.72 to 1.78  $\text{Mg m}^{-3}$  across the treatments under CT and RT, respectively. Among the treatments, sole organic treatment (viz., T5) significantly lowered the bulk density ( $1.73 \text{ Mg m}^{-3}$ ), which was at par with T4 ( $1.73 \text{ Mg m}^{-3}$ ). Among the physical soil parameters, mean weight diameter of the aggregates, which is a reflection of stability of the aggregates, is a crucial indicator of soil quality (Kutilek 2004), especially in rainfed Alfisols, affecting soil sustainability and crop production. In the present study, mean weight diameter of the soil aggregates varied from 0.11 to 0.18 mm across the treatments. Irrespective of the tillage, the performance of sole organic treatment (T5) was superior to sole inorganic treatment in improving the mean weight diameter (0.15 mm) of the soil aggregates.

**Table 3.** Long-term effects of tillage and conjunctive nutrient management treatments on soil physical and physicochemical parameters under sorghum–mung bean cropping in Alfisols of Hyderabad

Tillage	Nutrient-use treatments	Bulk density (Mg m <sup>-3</sup> )	MWD (mm)	HC (cm h <sup>-1</sup> )	pH	EC (dS m <sup>-1</sup> )	OC (g kg <sup>-1</sup> )
Conventional tillage	T1	1.80	0.11	3.27			
	T2	1.74	0.12	3.78	6.31	0.06	5.6
	T3	1.74	0.14	3.87	6.27	0.05	6.0
	T4	1.74	0.12	3.83	6.85	0.13	6.2
	T5	1.73	0.13	4.08	6.54	0.06	6.3
Reduced tillage	T1	1.78	0.12	2.28	6.59	0.09	6.5
	T2	1.74	0.13	2.61	6.82	0.06	5.7
	T3	1.74	0.16	2.90	6.62	0.07	6.1
	T4	1.72	0.13	2.82	6.64	0.08	7.0
	T5	1.72	0.18	3.32	6.64	0.07	6.6
LSD ( $P < 0.05$ )	Between tillage means	NS	NS	0.16	6.75	0.08	7.2
	Between treatment means	0.03	0.017	0.17	0.14	NS	NS
	Between two treatment means at same tillage	NS	NS	NS	NS	.027	0.37
	Between two treatment means at same or different treatments	NS	NS	NS	NS	NS	NS
					NS	NS	NS

*Note.* T1 = control; T2 = 40 kg N through urea; T3 = 4 Mg compost + 20 kg N through urea; T4 = 2 Mg Gliricidia loppings + 20 kg N through urea; T5 = 4 Mg compost + 2 Mg gliricidia loppings.

The improvement in the mean weight diameter under sole organic treatment may be attributed to the addition of organic matter and release of metabolic by-products during the process of decomposition of organics. Also, most of the plant residues provide a fresh C source for microbial biomass production, which has been shown to increase soil aggregation through several different mechanisms (Smith and Elliott 1990). The key role played by organic matter in soil aggregation and structural stability has also been comprehensively documented earlier (Horn et al. 1995; Carter and Stewart 1996). Contrarily, Jiao et al. (2006) reported that fertilizer application often increases soil aggregations through their influence on crop production because more crop residues are returned to fertilized than unfertilized soils (Gregorich et al. 1996; Campbell et al. 2001). Hydraulic conductivity, another important soil-quality indicator, varied from 3.27 to 4.08 and 2.28 to 3.32 cm h<sup>-1</sup> across the treatments (Table 3). Conventional tillage showed a significant influence on the hydraulic conductivity compared to RT. Of all the treatments studied, the significantly highest soil hydraulic conductivity (3.7 cm h<sup>-1</sup>) was observed under sole organic treatment (viz., T5). It was interesting to observe that this treatment played an important role in ameliorating or modifying the soil bulk density, mean weight diameter of the aggregates, and hydraulic conductivity.

### Chemical Soil-Quality Attributes

The long-term influences of the tillage and conjunctive nutrient-use treatments were also measured on chemical parameters (Tables 3 and 4). In the present study, no significant effect of tillage was recorded on chemical parameters except pH, available sulfur (S), and DTPA-extractable Mn. However, the conjunctive nutrient-use treatments had a significant effect on all the chemical parameters studied except pH and Ca. The combined interactive effects of tillage and conjunctive nutrient-use treatments were significant only in the case of available P, K, and DTPA-extractable Zn and Fe.

Reduced tillage plots recorded significantly higher soil pH compared to CT, which is a desirable feature for these Alfisols having soil pH nearing the slightly acidic range (6.27 to 6.82). However, conjunctive nutrient-use treatments had no significant influence on pH. Fließbach et al. (2007) reported an increase in soil pH under organic systems, whereas the integrated systems had the lowest pH values. Electrical conductivity in the soils varied from 0.05 to 0.13 dS m<sup>-1</sup> across the treatments and was highest under T3 (0.13 dS m<sup>-1</sup>) which may not be undesirable. Organic C maintenance is considered to be a rather difficult task in these SAT Alfisols. The importance of soil organic C as an important attribute in monitoring soil quality has been emphasized by several researchers

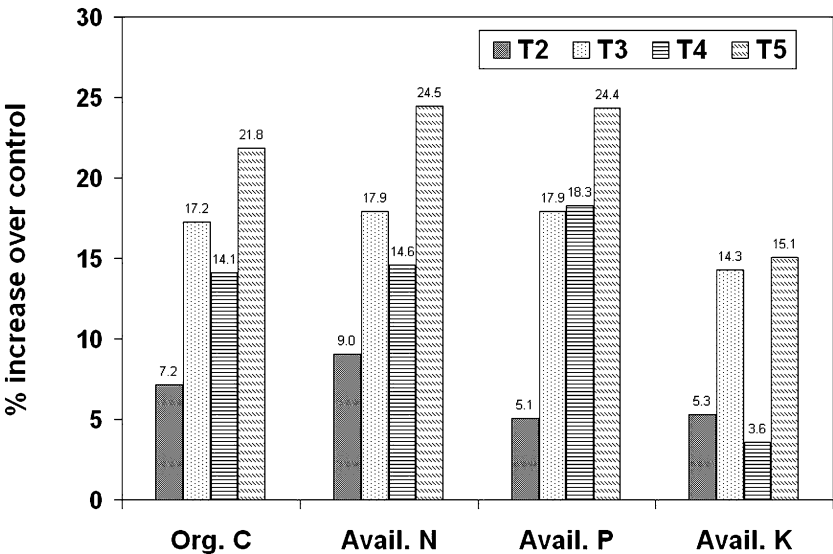
**Table 4.** Long-term effects of tillage and conjunctive nutrient management treatments on chemical soil-quality parameters under sorghum–mung bean cropping in Alfisols of Hyderabad

Tillage	Nutrient-use treatments	N	P (kg ha <sup>-1</sup> )	K	Ca (cmol kg <sup>-1</sup> )	Mg (µg g <sup>-1</sup> )	S (µg g <sup>-1</sup> )	Zn	Fe	Cu (µg g <sup>-1</sup> )	Mn	B
Conventional tillage	T1	144.32	31.75	134.58	2.97	1.17	8.38	0.88	8.43	0.82	11.79	0.41
	T2	156.43	30.18	140.92	3.48	1.54	13.13	1.10	10.68	1.08	16.46	0.66
	T3	168.40	31.21	164.05	4.69	1.48	8.67	1.15	10.63	1.07	15.30	0.82
	T4	162.82	36.62	140.58	3.35	1.51	10.93	1.17	9.57	0.89	12.97	0.95
	T5	170.45	36.78	147.00	3.72	1.39	9.86	1.28	7.56	0.91	11.96	0.75
Reduced tillage	T1	146.34	23.19	136.39	3.67	0.80	8.04	0.85	6.60	0.81	10.99	0.35
	T2	160.46	27.54	144.39	3.72	1.11	13.06	1.05	11.39	1.02	14.49	0.70
	T3	174.37	33.57	145.64	3.56	1.32	11.47	1.18	8.68	0.93	13.06	0.84
	T4	170.22	29.37	140.13	3.57	1.20	12.83	1.42	12.13	0.98	10.93	0.98
	T5	191.37	31.54	164.76	3.74	1.73	12.60	1.29	7.15	0.83	11.21	0.76
LSD ( <i>P</i> < 0.05)	Between tillage means	NS	NS	NS	NS	NS	1.09	NS	NS	NS	1.42	NS
	Between treatment means	8.22	3.08	9.38	NS	0.13	1.44	0.065	1.27	0.087	1.30	0.036
	Between two treatment means at same tillage	NS	4.36	13.26	NS	NS	NS	0.092	1.80	NS	NS	NS
	Between two treatment means at same or different tillage	NS	5.48	20.45	NS	NS	NS	0.088	1.64	NS	NS	NS

*Note.* T1 = control; T2 = 40 kg N through urea; T3 = 4 Mg compost + 20 kg N through urea; T4 = 2 Mg Gliricidia loppings + 20 kg N through urea; T5 = 4 Mg compost + 2 Mg gliricidia loppings.

(Brejda et al. 2000; Shukla, Lal, and Ebinger 2006; Zhang and Fang 2007). In the present study, organic C ranged from 5.6 to 7.2 g kg<sup>-1</sup>, whereas soil-available N varied between 144.4 and 191.4 kg ha<sup>-1</sup> across the treatments. Tillage did not show any significant effect on the soil organic C as well as available N. The conjunctive nutrient-use treatments significantly increased both organic C and available N in soil when compared with control. Irrespective of the tillage, T5 showed highest amounts of soil organic C (6.8 g kg<sup>-1</sup>) and available N (180.91 kg ha<sup>-1</sup>), thus registering an increase of 21.6% and 24.5% respectively, over control. The next best treatment option (viz., T3) was also quite effective in improving the organic C and available N to the extent of 17% and 17.9% compared to control (Figure 2). Contrary to the earlier studies (Liebig, Tanaka, and Wienhold 2004; Astier et al. 2006; Roldán et al. 2007), in the present study, even RT could not improve the organic C and available N status. This was attributed to high temperature-mediated fast oxidation in these SAT soils. Hence, any management practice that helps improve these two indicators is considered a benefit for this region.

Available P and K in the soils ranged between 23.19 and 36.78 kg ha<sup>-1</sup> and between 134.58 and 164.8 kg ha<sup>-1</sup>, respectively, across the treatments (Table 4). Exchangeable Ca in the soil ranged between 2.97 and 4.69 cmol kg<sup>-1</sup>, whereas exchangeable Mg ranged between 0.80 and 1.73 cmol kg<sup>-1</sup>. Tillage had no significant influence on available P, K, and also exchangeable Mg, whereas the effects of conjunctive nutrient-



**Figure 2.** Changes in organic carbon and available nutrients over unamended control as influenced by conjunctive nutrient-use treatments.

use treatment were significant. When averaged over tillage, T5 proved quite superior in maintaining the highest amount of available P ( $34.2 \text{ kg ha}^{-1}$ ), K ( $155.9 \text{ kg ha}^{-1}$ ), and exchangeable Mg ( $1.56 \text{ cmol kg}^{-1}$ ) among the treatments studied. Tillage did not show any significant influence also on the micronutrient contents of soils except in the case of Mn, whereas the conjunctive nutrient-use treatments had significant influence on all the micronutrients (Table 4). Of all the treatments, conjunctive application of T4 recorded the significantly highest available Zn ( $1.29 \mu\text{g g}^{-1}$ ) and B ( $0.96 \mu\text{g g}^{-1}$ ). Some earlier reports also revealed that the integrated application of plant nutrients through farm yard manure (FYM) along with fertilizer NPK plays a significant role in increasing the available soil micronutrients (viz., Zn, Fe, Mn, and Cu) (Prasad and Singh 1980) and also in sustaining soil fertility and crop productivity (Chand, Anwar, and Patra, 2006). In the present study, the conjunctive nutrient application also significantly increased available Zn and B in the soil.

### Biological Soil-Quality Attributes

Apart from physical and chemical soil-quality parameters, the biological parameters, despite being difficult to measure, predict, or quantify, play the predominant role in influencing soil quality. In the present study, the long-term effects of tillage and conjunctive nutrient-use treatments on biological soil-quality parameters [viz., dehydrogenase assay (DHA), microbial biomass carbon (MBC), labile carbon (LC), and microbial biomass nitrogen (MBN)] were monitored (Table 5). Tillage did not influence any of the soil biological parameters, whereas the sole and conjunctive use of organic and inorganic sources of nutrients showed a significant influence. Interestingly, tillage in combination with the conjunctive nutrient treatments (tillage  $\times$  treatments) had a significant influence on DHA and LC contents of the soils.

Soil enzymes have been suggested as potential indicators or signals of soil quality because of their essential role in soil management and inducing changes in soil fertility (Benitez et al. 2006; Melero et al. 2006, 2007). Dehydrogenase is an oxidoreductase enzyme, and the importance of it as one of the soil-quality indicators has been emphasized (Nannipieri 1994; Roldán et al. 2005). In the present study, DHA in the soil varied from  $1.29$  to  $2.60 \mu\text{g triphenyl formazone (TPF) h}^{-1}\text{g}^{-1}$  across the treatments. The influence of tillage on DHA activity was not statistically significant. However, when averaged over tillage, the influence of nutrient-use treatments was significant and was highest under T5 ( $2.18 \mu\text{g TPF h}^{-1}\text{g}^{-1}$ ) followed by T4 ( $2.02 \mu\text{g TPF h}^{-1}\text{g}^{-1}$ ). Earlier, Manna et al. (2005) observed an increase in dehydrogenase activity with the application of fertilizers and conjunctive use of fertilizer with organic



**Table 5.** Long-term effects of tillage and conjunctive nutrient management treatments on soil biological parameters under sorghum–mung bean cropping in Alfisols of Hyderabad

Tillage	Nutrient-use treatments	Dehydrogenase assay ( $\mu\text{g TPF h}^{-1}\text{g}^{-1}$ )	Microbial biomass carbon ( $\mu\text{g g}^{-1}$ of soil)	Labile carbon ( $\text{mg kg}^{-1}$ )	Microbial biomass nitrogen ( $\text{kg ha}^{-1}$ )
Conventional tillage	T1	1.51	115.10	203.11	42.35
	T2	1.94	142.86	245.85	52.58
	T3	1.83	152.66	231.76	56.21
	T4	1.84	152.68	244.51	56.19
	T5	1.77	162.40	257.03	59.81
Reduced tillage	T1	1.29	125.87	230.90	46.05
	T2	1.57	151.25	246.52	55.33
	T3	1.53	155.83	232.74	57.02
	T4	2.20	163.59	244.93	59.85
	T5	2.60	172.03	264.98	62.93
LSD ( $P<0.05$ )	Between tillage means	NS	NS	NS	NS
	Between treatment means	0.16	7.72	9.42	2.85
	Between two treatment means at same tillage	0.23	NS	13.33	NS
	Between two treatment means at same or different treatments	0.23	NS	12.85	NS

*Note.* T1 = control; T2 = 40 kg N through urea; T3 = 4 Mg compost + 20 kg N through urea; T4 = 2 Mg Gliricidia loppings + 20 kg N through urea; T5 = 4 Mg compost + 2 Mg gliricidia loppings.

sources of nutrients such as FYM under subhumid and SAT soils. In the present study, we could clearly observe the influence of organic sources of nutrients on dehydrogenase activity, whereas the influence of CT and RT did not vary significantly, which was also reported by Marschner, Kandeler, and Marschner (2003).

Soil microbial biomass C and N followed a trend similar to that observed for soil organic C with respect to tillage and conjunctive nutrient-use treatments. Microbial biomass C in these soils varied from 115.10 to 172.0  $\mu\text{g g}^{-1}$  soil across the treatments. In the present study, the effect of tillage on microbial biomass C was not significant; nevertheless, RT tended to maintain relatively higher amounts of microbial biomass C compared to CT. Some of the earlier studies have also indicated the superiority of no-tillage or RT in improving the microbial biomass C in soils (Sparrow, Lewis, and Knight 2006; Franchini et al. 2007). Among the conjunctive nutrient-use treatments, application of T5 recorded the highest microbial biomass C content of 162.40 and 172.03  $\mu\text{g g}^{-1}$  of soil under both CT and RT, respectively, followed by T4 under CT (152.68  $\mu\text{g g}^{-1}$  of soil) and RT (163.59  $\mu\text{g g}^{-1}$  of soil). Schjønning et al. (2002) and Melero et al. (2007) also reported higher microbial biomass C in organically fertilized soils. In the present study, it was interesting to note that the plots that received N as the sole inorganic fertilizer showed significantly less microbial biomass C than other treatments (Masto et al. 2006). The probable reasons for the lesser amount of microbial biomass C in the fertilized conditions may be due to less extensive root system and less belowground plant biomass under readily available nutrient conditions (Biederbeck, Campbell, and Zentner 1984), soil acidification (Ladd et al. 1994), and interference of high levels of inorganic nutrients and lower pH with biochemical assay during estimation of microbial biomass (Widmer, Brookes, and Parry 1989; Amato and Ladd 1994). Soil microbial biomass C has been considered an important and sensitive indicator for soil quality because it is biologically meaningful, sensitive to management or pollution, measurable (Powelson 1994; Schlöter, Dilly, and Munich 2003), and an important source and sink for the majority of the nutrients available to plants, thus influencing the growth and development of crops (Dalal 1998; Wardle et al. 1999; Spedding et al. 2004; Roldán et al. 2007).

Other important biological parameters monitored were  $\text{KMnO}_4$ -oxidizable (labile) C and microbial biomass N (MBN). Labile organic-matter pools can be considered indicators of soil quality that influence soil function in specific ways and that are much more sensitive to changes in soil management practice (Haynes 2005). In our study, labile C in the soils ranged from 203.11 to 264.98  $\text{mg kg}^{-1}$ , whereas MBN varied from 42.35 to 62.93  $\text{kg ha}^{-1}$  across the treatments. Of all the treatments, sole organic sources of nutrients applied through T5 recorded the highest

labile C content of 261.0 mg kg<sup>-1</sup> and MBN of 61.4 kg ha<sup>-1</sup>. More vividly, sole organic nutrient management treatment increased DHA activity by 56.1%, microbial biomass C by 38.8 %, LC by 20.3%, and MBN by 38.8% over the unamended control and proved superior in improving biological soil health indicators (Figure 3).

CONCLUSIONS

Our study has clearly indicated that even after 8 years, CT remained significantly superior to RT in maintaining higher yields and SYI of sorghum and mung bean crops. The effect of conjunctive use of organic and inorganic source of nutrients on crop yields and SYI was also quite conspicuous. The general trend of performance of the conjunctive nutrient-use treatments in terms of grain yield remained in the order of T4 = T3 = T2 > T5 > T1 in the case of sorghum and T3 > T5 = T4 > T2 > T1 in the case of mung bean. While considering the soil-quality parameters, tillage did not play much role in influencing the soil-quality parameters, except in a few cases. Among the nutrient-use treatments, T5 was found to be superior in influencing the majority of the soil-quality parameters, especially biological indicators. Thus, the farmers have the option to choose either of the treatment combinations of T3, T4, and T5 to meet the goals of saving on fertilizer N by 50%, getting better yields with a greater degree of sustainability over a long-term basis, and improving soil-quality parameters.

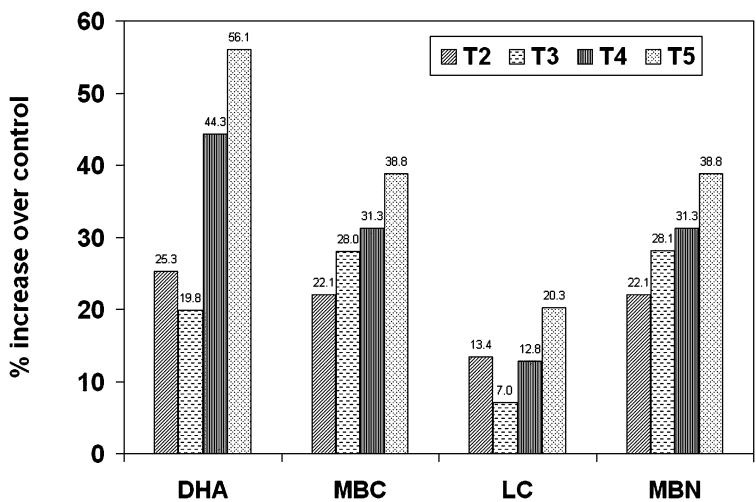


Figure 3. Improvement in biological soil-quality indicators over unamended control as influenced by conjunctive nutrient-use treatments.

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## REFERENCES

- Amato, M., and J. N. Ladd. 1994. Application of the ninhydrin-reactive N assay for microbial biomass in acid soils. *Soil Biology and Biochemistry* 26:1109–1115.
- Astier, M., J. M. Maass, J. D. Etchevers-Barra, J. J. Peña, and F. de León González. 2006. Short-term green manure and tillage management effects on maize yield and soil quality in an Andisol. *Soil and Tillage Research* 88 (1–2): 153–159.
- Bansal, R. K., N. K. Awadhwai, and V. M. Mayande. 1987. Implement development for SAT Alfisols. In *Alfisols in the semi-arid tropics: Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils*, 97–107. India: ICRISAT Centre. Patancheru, Andhra Pradesh 502324, India.
- Baumhardt, R. L., and O. R. Jones. 2002. Residue management and paratillage effects on some soil properties and rain infiltration. *Soil and Tillage Research* 65:19–27.
- Benitez, E., R. Nogales, M. Campos, and F. Ruano. 2006. Biochemical variability of olive-orchard soils under different management systems. *Applied Soil Ecology* 32:221–231.
- Biederbeck, V. O., C. A. Campbell, and R. P. Zentner. 1984. Effect of crop rotation and fertilization on some biological properties of a loam in southwestern Saskatchewan. *Canadian Journal of Soil Science* 64:355–367.
- Blake, G. R., and K. H. Hartge. 1986. Bulk density. In *Methods of soil analysis, part 1: Physical and mineralogical methods*, 2nd ed., ed. A. Klute, 364–367. Madison, Wisc.: ASA and SSSA.
- Bokhtiar, S. M., and K. Sakurai. 2005. Effects of organic manure and chemical fertilizer on soil fertility and productivity of plant and ratoon crops of sugarcane. *Archives of Agronomy and Soil Science* 51 (3): 325–334.
- Brejda, J. J., T. B. Moorman, D. L. Karlen, and T. H. Dao. 2000. Identification of regional soil quality factors and indicators, I: Central and southern high plains. *Soil Science Society of America Journal* 64:2115–2124.
- Campbell, C. A., F. Selles, G. P. Lafond, V. Q. Biederbeck, and R. P. Zentner. 2001. Tillage–fertilizer changes: Effect on some soil quality attributes under long-term crop rotations in a thin Black Chernozem. *Canadian Journal of Soil Science* 81:157–165.

- Carter, M. R., and B. A. Stewart. 1996. *Structure and organic matter storage in agricultural soils*. Boca Raton, FL: Lewis/CRC Press.
- Chand, S., M. Anwar, and D. D. Patra. 2006. Influence of long-term application of organic and inorganic fertilizer to build up soil fertility and nutrient uptake in mint–mustard cropping sequence. *Communications in Soil Science and Plant Analysis* 37:63–76.
- Charreau, C. 1977. Controversial points in dryland farming practices in semi-arid West Africa. In *Symposium on Rainfed Agricultural Semi-arid Regions*, ed. G. H. Cannell, 313–360. Riverside, Calif.: University of California, Riverside.
- Cocheme, J., and P. Franquin. 1967. *An agroclimatology survey of a semiarid area in Africa south of the Sahara* (FAO/Unesco/Wmo Interagency Project on Agroclimatology Technical Note 86–160). Rome, Italy: FAO.
- Dalal, R. C. 1998. Soil microbial biomass—What do the numbers really mean? *Australian Journal of Experimental Agriculture* 38:649–665.
- De Vita, P., E. Di Paolo, G. Fecondo, N. Di Fonzo, and M. Pisante. 2007. No-tillage and conventional tillage effects on durum wheat yield, grain quality, and soil moisture content in southern Italy. *Soil and Tillage Research* 92 (1–2): 69–78.
- El-Swaify, S. A., S. Singh, and P. Pathak. 1983. Physical and conservation constraints and management components for SAT Alfisols. In *ALFISOLS in the Semi-arid Tropics: Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils*. Patancheru, Andhra Pradesh, India: ICRISAT Centre.
- FAO. 1989. *Sustainable agricultural production: Implications for international agricultural research* (Research and Technology Paper No. 4). Rome, Italy: FAO.
- Fließbach, A., H. R. Oberholzer, L. Gunst, and P. Mäder. 2007. Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. *Agriculture, Ecosystems and Environment* 118 (1–4): 273–284.
- Franchini, J. C., C. C. Crispino, R. A. Souza, E. Torres, and M. Hungria. 2007. Microbiological parameters as indicators of soil quality under various soil management and crop rotation systems in southern Brazil. *Soil and Tillage Research* 92 (1–2): 18–29.
- Govaerts, B., M. Mezzalama, K. D. Sayre, J. Crossa, J. M. Nicol, and J. Deckers. 2006. Long-term consequences of tillage, residue management, and crop rotation on maize/wheat root rot and nematode populations in subtropical highlands. *Applied Soil Ecology* 32 (3): 305–315.
- Govaerts, B., M. Mezzalama, Y. Unno, K. D. Sayre, M. Luna-Guido, K. Vanherck, L. Dendooven, and J. Deckers. 2007. Influence of tillage, residue management, and crop rotation on soil microbial biomass and catabolic diversity. *Applied Soil Ecology* 37 (1–2): 18–30.
- Gregorich, E. G., B. H. Ellert, C. F. Drury, and B. C. Liang. 1996. Fertilization effects on soil organic matter turnover and corn residue C storage. *Soil Science Society of America Journal* 60:472–476.
- Hanway, J. J., and H. Heidel. 1952. Soil analyses methods as used in Iowa State College soil testing laboratory. *Iowa Agric.* 57:1–31.
- Haynes, R. J. 2005. Labile organic matter fractions as central components of the quality of agricultural soils: An overview. *Advances in Agronomy* 85:221–268.

- Horn, R., H. Domżzał, A. Słowińska-Jurkiewicz, and C. van Ouwerkerk. 1995. Soil compaction processes and their effects on the structure of arable soils and the environment. *Soil and Tillage Research* 35 (1–2): 23–36.
- Hulugalle, N. R., and P. R. Maurya. 1991. Tillage systems for the West African semiarid tropics. *Soil and Tillage Research* 20:187–199.
- Jenkinson, D. S., and J. N. Ladd. 1981. Microbial biomass in soil: Measurement and turnover. In *Soil biochemistry*, ed. E. A. Paul and J. N. Ladd, vol. 5, 415–471. New York: Marcel Dekker.
- Jenkinson, D. S., and D. S. Powlson. 1976. The effects of biocidal treatments on metabolism in soil, V: A method for measuring soil biomass. *Soil Biology and Biochemistry* 8:209–213.
- Jiao, Y., K. Joann, J. K. Whalen, and W. H. Hendershot. 2006. No-tillage and manure applications increase aggregation and improve nutrient retention in a sandy-loam soil. *Geoderma* 134:24–33.
- Kampen, J., and J. Burford. 1980. Production systems, soil-related constraints, and potential in the semi-arid tropics, with special reference to India. In *Priorities for alleviating soil-related constraints to food production in the tropics*. International Rice Research Institute, Los Banos, Laguna, Philippines: 141–165.
- Khan, A., D. Chandra, P. Nanda, S. Singh, and A. Ghorai. 2004. Integrated nutrient management for sustainable rice production. *Archives of Agronomy and Soil Science* 50 (2): 161–165.
- Klute, A. 1965. Laboratory measurement of hydraulic conductivity of saturated soil. In *Methods of soil analysis, part I*, ed. C. A. Black, 210–211. Madison, Wisc.: American Society of Agronomy.
- Kutilek, M. 2004. Soil hydraulic properties as related to soil structure. *Soil and Tillage Research* 79 (2): 175–184.
- Ladd, J. N., M. Amato, Z. Li-Kai, and J. E. Schultz. 1994. Differential effects of rotation, plant residue, and nitrogen fertilizer on microbial biomass and organic matter in an Australian Alfisol. *Soil Biology and Biochemistry* 26:821–831.
- Lal, R. 1997. Long-term tillage and maize monoculture effects on a tropical Alfisol in western Nigeria, I: Crop yield and soil physical properties. *Soil and Tillage Research* 42 (3): 145–160.
- Lal, R. 1998. *Soil Quality and Agricultural Sustainability*. Ann Arbor Press: Chelsea, MI.
- Lenhard, G. 1956. Die dehydrogenase-aktivitat des Bodens als Mass fur die mikroorganismen-tatigkeit im Boden. *Zeitschrift fur Pflanzenernaehr. Dueng und Bodenkd* 73:1–11.
- Liebig, M. A., D. L. Tanaka, and B. J. Wienhold. 2004. Tillage and cropping effects on soil quality indicators in the northern Great Plains. *Soil and Tillage Research* 78 (2): 131–141.
- Lindsay, W. L., and W. A. Norvell. 1978. Development of a DTPA soil test for zinc, iron, manganese and copper. *Soil Science Society of America Journal* 42:421–428.
- Manna, M. C., A. Swarup, R. H. Wanjari, H. N. Ravankar, B. Mishra, M. N. Saha, Y. V. Singh, D. K. Sahi, and P. A. Sarap. 2005. Long-term effect of fertilizer and manure application on soil organic carbon storage, soil quality,

- and yield sustainability under sub-humid and semi-arid tropical India. *Field Crops Research* 93:264–280.
- Marschner, S., E. Kandeler, and B. Marschner. 2003. Structure and function of the soil microbial community in a long-term fertilizer experiment. *Soil Biology and Biochemistry* 35 (3): 453–461.
- Masto, R. E., P. K. Chhonkar, D. Singh, and A. K. Patra. 2006. Changes in soil biological and biochemical characteristics in a long-term field trial on a subtropical Inceptisol. *Soil Biology and Biochemistry* 38:1577–1582.
- Melero, S., E. Madejon, J. C. Ruiz, and J. F. Herencia. 2007. Chemical and biochemical properties of a clay soil under dryland agriculture system as affected by organic fertilization. *European Journal of Agronomy* 26:327–334.
- Melero, S., J. C. Ruiz Porras, J. F. Herencia, and E. Madejon. 2006. Chemical and biochemical properties in a silty loam soil under conventional and organic management. *Soil and Tillage Research* 90:162–170.
- Miller, R. O., B. Vaughan, and J. Kutoby-Amacher. 2000. Extraction of soil boron with DTPA–sorbitol. *The Soil-Plant Analyst* Spring 4–5: 10.
- Nannipieri, P. 1994. The potential use of soil enzymes as indicators of productivity, sustainability, and pollution. In *Soil biota: Management in sustainable farming systems*, ed. C. E. Pankhurst, B. M. Doube, V. V. S. R. Gupta, and P. R. Grace, 238–244. Collingwood, Australia: CSIRO.
- Olsen, S. R., C. U. Cole, F. S. Watanabe, and L. A. Deen. 1954. *Estimation of available phosphorus in soil by extracting with sodium bicarbonate* (USDA Circular 939). Washington, D.C.: U.S. Government Printing Office.
- Powlson, D. S. 1994. The soil microbial biomass: Before, beyond, and back. In *Beyond the biomass*, ed. K. Ritz, J. Dighton, and K. E. Giller, 3–20. Chichester, U.K.: Wiley.
- Prasad, B., and A. P. Singh. 1980. Changes in soil properties with long-term use of fertilizer, lime, and farmyard manure. *Journal of Indian Society of Soil Science* 28:465–468.
- Rhoades, J. D. 1982. Soluble salts. In *Methods of soil analysis, part 2: Chemical and microbiological properties*, 2nd ed., ed. A. L. Page, R. H. Miller, and D. R. Keeney, 635–655. Madison, Wisc.: ASA and SSSA.
- Roldán, A., J. R. Salinas-García, M. M. Alguacil, A. Diaz, and F. Caravaca. 2005. Soil enzyme activities suggest advantages of conservation tillage practices in sorghum cultivation under subtropical conditions. *Geoderma* 129:178–185.
- Roldán, A., J. R. Salinas-García, M. M. Algucil, and F. Caravaca. 2007. Soil sustainability indicators following conservation tillage practices under sub-tropical maize and bean crops. *Soil and Tillage Research* 93:273–282.
- Schjørring, P., S. Elmholt, L. J. Munkholm, and K. Debosz. 2002. Soil quality aspects of humid sandy loams as influenced by organic and conventional long-term management. *Agriculture, Ecosystems and Environment* 88 (3): 195–214.
- Schlöter, M., O. Dilly, and J. C. Munich. 2003. Indicators for evaluating soil quality. *Agriculture, Ecosystems and Environment* 98:255–262.
- Sharma, K. L., U. K. Mandal, K. Srinivas, K. P. R. Vittal, B. Mandal, J. Kusuma Grace, and V. Ramesh. 2005. Long-term soil management effects on crop yields and soil quality in a dryland Alfisol. *Soil and Tillage Research* 83:246–259.
- Shukla, M. K., R. Lal, and M. Ebinger. 2006. Determining soil quality indicators by factor analysis. *Soil and Tillage Research* 87:194–204.

- Singh, R. P., S. K. Das, U. M. Bhaskara Rao, and M. Narayana Reddy. 1990. *Towards sustainable dryland agricultural practices* (Technical Bulletin). Hyderabad, India: Central Research Institute for Dryland Agriculture.
- Smith, J. L., and L. F. Elliott. 1990. Tillage and residue management effects on soil organic matter dynamics in semi arid regions. *Advances in Soil Science* 13:69–85.
- Snedecor, G., W. Cochran, and D. Cox. 1989. *Statistical methods*, 8th ed. Ames, Iowa: Iowa State University Press.
- Sparrow, S. D., C. E. Lewis, and C. W. Knight. 2006. Soil quality response to tillage and crop residue removal under subarctic conditions. *Soil and Tillage Research* 91 (1–2): 15–21.
- Spedding, T. A., C. Hamel, G. R. Mehuys, and C. A. Madramootoo. 2004. Soil microbial dynamics in maize-growing soil under different tillage and residue management systems. *Soil Biology and Biochemistry* 36:499–512.
- Subbaiah, B. V., and G. C. Asija. 1956. A rapid procedure for determination of available nitrogen in soils. *Current Science* 25:259–260.
- Tsuji, H., H. Yamamoto, K. Matsuo, and K. Usuki. 2006. The effects of long-term conservation tillage, crop residues, and P fertilizer on soil conditions and responses of summer and winter crops on an Andosol in Japan. *Soil and Tillage Research* 89:167–176.
- Unger, P. W. 1990. Conservation tillage systems. In *Advances in soil science: Dryland agriculture strategies for sustainability*, ed. R. P. Singh, J. F. Parr, and B. A. Stewart, vol. 13, 28–57. New York: Springer-Verlag.
- van Bevel, C. H. M. 1949. Mean weight diameter of soil aggregates as a statistical index of aggregation. *Soil Science Society of America Proceedings* 14:20–23.
- Walkley, A. J., and C. A. Black. 1934. Estimation of organic carbon by chromic acid titration method. *Soil Science* 37:29–38.
- Wardle, D. A., G. W. Yeates, K. S. Nicholson, K. I. Bonner, and R. N. Watson. 1999. Response of soil microbial biomass dynamics, activity, and plant litter decomposition to agricultural intensification over a seven-year period. *Soil Biology and Biochemistry* 31:1707–1720.
- Weil, R. R., K. R. Islam, M. A. Stine, J. B. Gruver, and S. E. Sampson-Liebeg. 2003. Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. *American Journal of Alternative Agriculture* 18 (1): 3–17.
- Widmer, P., P. C. Brookes, and L. C. Parry. 1989. Microbial biomass C and readily mineralized nitrogen in peat and forest humus. *Soil Biology and Biochemistry* 20:579–581.
- Yoder, R. E. 1936. A direct method of aggregate analysis and study of the physical nature of erosion losses. *Journal of American Society of Agronomy* 28:337–351.
- Zhang, M. K., and L. P. Fang. 2007. Effect of tillage, fertilizer, and green manure cropping on soil quality at an abandoned brick making site. *Soil and Tillage Research* 93 (1): 87–93.